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Alignment between seafloor spreading directions and absolute plate motions through time

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Abstract

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Key Points:

- Analysis of alignment between relative and absolute plate motions from 130 Ma to present day
- This alignment is strongest in ocean basins where the influence of slab-pull forces is smallest
- Spreading fabric can be used to improve global absolute plate motion models

Supporting Information:

- Figure S1 and Table S1

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Alignment between seafloor spreading directions and absolute plate motions through time

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Abstract The history of seafloor spreading in the ocean basins provides a detailed record of relative motions between Earth's tectonic plates since Pangea breakup. Determining how tectonic plates have moved relative to the Earth's deep interior is more challenging. Recent studies of contemporary plate motions have demonstrated links between relative plate motion and absolute plate motion (APM), and with seismic anisotropy in the upper mantle. Here we explore the link between spreading directions and APM since the Early Cretaceous. We find a significant alignment between APM and spreading directions at mid-ocean ridges; however, the degree of alignment is influenced by geodynamic setting, and is strongest for mid-Atlantic spreading ridges between plates that are not directly influenced by time-varying slab pull. In the Pacific, significant mismatches between spreading and APM direction may relate to a major plate-mantle reorganization. We conclude that spreading fabric can be used to improve models of APM.

1. Introduction

Recent seismological experiments have provided powerful new constraints on the links between mid-ocean ridge (MOR) processes, absolute plate motions, and mantle flow. Global anisotropic seismic tomography models show correlations between S_{SV} fast axes and both fossil spreading fabric and present-day absolute plate motion (APM), the latter more apparent at greater depths and near MORs [*Becker et al.*, 2014; *Beghein et al.*, 2014]. A detailed study of anisotropy beneath ridge segments on the East Pacific Rise [*Toomey et al.*, 2007] shows fast axes closely aligned with plate spreading direction. Low-velocity fingers imaged at the base of the oceanic asthenosphere have been interpreted as regions of channelized mantle flow aligned with present-day APM [*French et al.*, 2013].

These observations provide strong evidence for a relationship between spreading direction, APM, and the state of the upper mantle. *Becker et al.* [2015] further suggested that minimizing the global misfit between APM and spreading direction at ridges defines a comprehensive reference frame. They showed that such an APM model matches seismic anisotropy, satisfies trench migration rates, and has a best fitting pole of net rotation similar to those previously determined from hot spots or geodynamic estimates. Direct seismic observations are limited to present-day Earth, but other geophysical data and plate tectonic reconstructions allow us to examine the relationship between spreading direction and APM as far back in time as there is preserved seafloor. Oceanic fracture zones, defined globally by gravity data derived from satellite altimetry [*Sandwell et al.*, 2014; *Matthews et al.*, 2011], record fossil spreading directions. Magnetic anomalies define fossil ridge axes and are compiled to produce global maps of seafloor age and spreading rate [*Muller et al.*, 2008] recording >200 Myr of relative plate motion (RPM).

Models of APM for the geological past have been derived based on hot spot tracks either assuming hot spot fixity [*Müller et al.*, 1993; *Wessel and Kroenke*, 2008; *Maher et al.*, 2015] or incorporating estimates of hot spot motion from geodynamic simulations [*Steinberger et al.*, 2004; *O'Neill et al.*, 2005; *Doubrovine et al.*, 2012], and based on the mapping of subducted slab remnants within seismic tomography [*van der Meer et al.*, 2010]. Here we use plate tectonic reconstructions combined with a range of alternative APM models to explore the alignment between seafloor spreading and APM since the Cretaceous. We focus on the following questions: How well does spreading align with APM? Does this alignment vary spatially and temporally? Are alignments stronger in some APM models than others, and does this evidence that some APM models might be more robust than others?

2. Formulation of Analysis

The spreading history of ocean basins is defined by magnetic anomaly isochrons and fracture zones, which are the primary constraints on plate tectonic reconstructions and seafloor age maps [*Muller et al.*, 2008; *Seton*

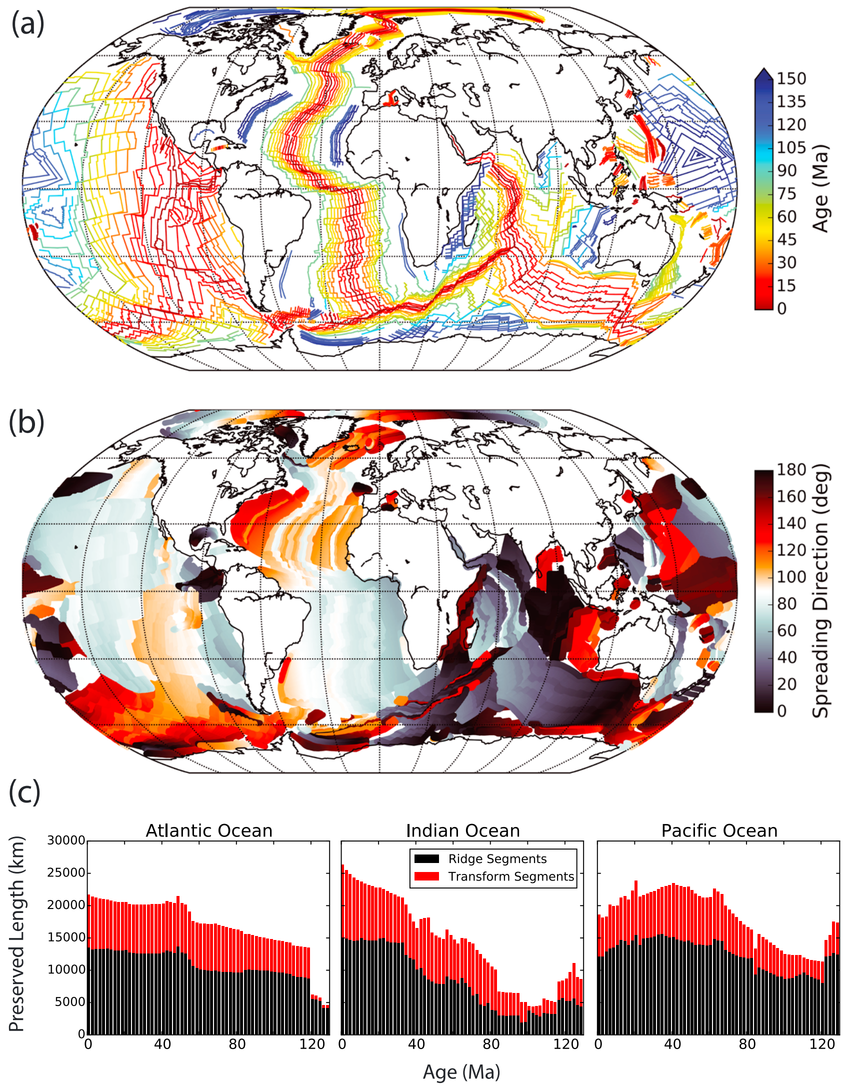

Figure 1. (a) Seafloor age isochrons from global plate tectonic reconstruction [*Müller et al.*, 2016]; (b) paleospreading direction along isochrons sampled regularly in time (2 Myr increment) and in space (0.25 arc degree along each line). Paleospreading directions (defined as clockwise from North) are determined from the relative plate motion parameters. (c) Total length of preserved isochrons for the main three ocean basins.

et al., 2012]. To determine paleospreading directions, previous studies have used the gradient of the seafloor age [*Debayle and Ricard*, 2013; *Becker et al.*, 2014].

We generate time-dependent measures of the angular mismatch between paleospreading and APM, which we refer to as skew following *Toomey et al.* [2007]. The set of isochrons from *Müller et al.* [2016] are spaced at irregular intervals corresponding to major, widely recognizable magnetic reversals (at 10.9 Ma, 20.1 Ma, 33.1 Ma, 40.1 Ma, 47.9 Ma, 55.9 Ma, 67.7 Ma, 83.0 Ma, 120.4 Ma, 126.7 Ma, and 130.5 Ma; all using the timescale of *Gee and Kent* [2007]), as well as additional isochrons within the Cretaceous Normal Superchron corresponding to interpreted changes in plate motion (Figure 1a). From these, we generate interpolated isochrons at 2 Myr intervals, then resample along each new line at an interval of 0.25 arc degree. Each line is encoded with information that specifies both the plate on which the isochron lies and the plate hosting the conjugate isochron. Spreading directions are determined from the Euler poles of rotation that specify the relative motion between these two plates at the time of each isochron. This method calculates the true plate divergence direction, whereas methods using the gradient of the seafloor age may produce incorrect spreading directions due to locally large age offsets across fracture zones and do not account for oblique spreading that characterizes a minority of slow-spreading

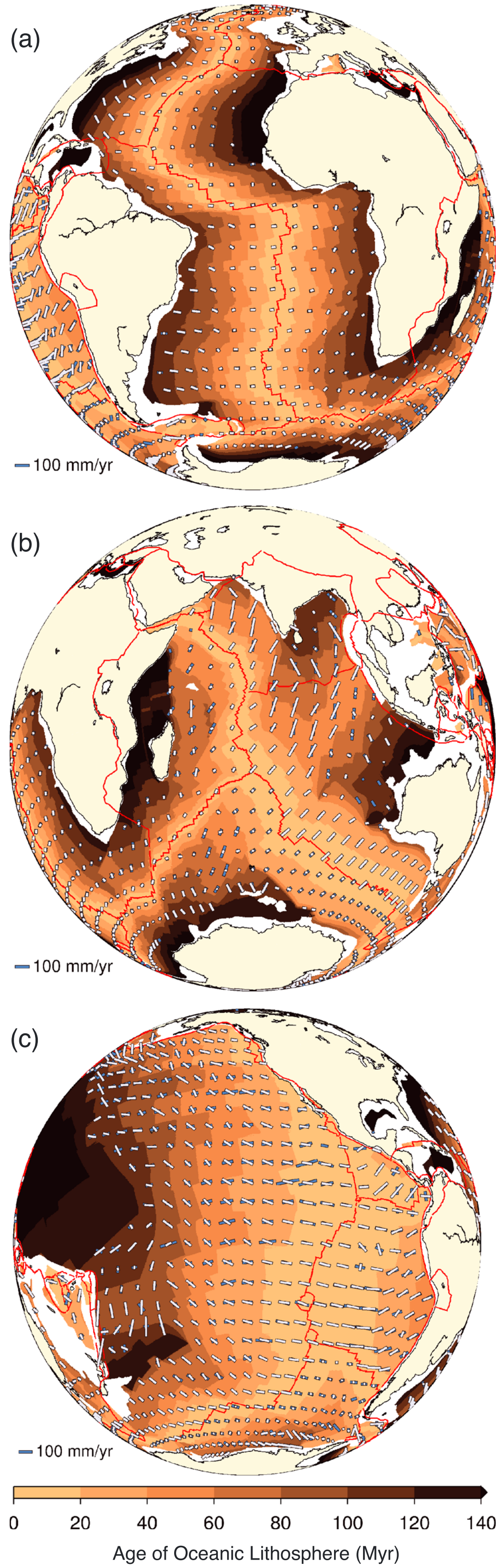

Figure 2. Paleospreading direction (white bars) and APM vector (blue bars) for the (a) Atlantic, (b) Indian, and (c) Pacific ocean basins based on APM model T2008 (APM models are compared in Figure 3). Bar length is proportional to velocity. For this figure only, APM vectors are reconstructed into the frame of reference of each plate; hence, their orientation does not represent the true direction at the time of the crust formed, but the angular difference between APM and paleospreading direction is preserved.

segments [*Montesi and Behn*, 2007]. The resulting set of spreading directions determined along consistently sampled isochrons are shown in Figure 1b, and the total length of preserved isochrons is shown in Figure 1c for each of the three major (Atlantic, Indian, and Pacific) ocean basins.

For each point within this isochron set, we calculate the APM motion vector at the time of each isochron, using average APM velocity vectors calculated over 5 Myr intervals. This focuses our analysis on APM for locations along MORs, analogous to the analysis of *Becker et al*. [2015] for the present day. The APM for isochrons on the African Plate (or the Pacific Plate, in the case of Pacific reference frames) can be determined directly from the APM model, otherwise it is determined via the same RPM model combined with each APM model [*Williams et al*., 2015]. We analyze the angular difference between the APM vector and the paleospreading direction (skew) as a function of plate age and ocean basin. To illustrate how the skew varies in space and time, Figure 2 shows APM direction vectors for seafloor of different ages reconstructed back to present-day coordinates, which together with paleospreading direction vectors reveal the angular skews for crust of all ages within each ocean basin (here for APM model T2008).

Calculations of the absolute motions of plate boundaries are dependent on the choice of APM model used [*Becker et al*., 2014; *Whittaker et al*., 2015; *Williams et al*., 2015]. We test a range of APM models, based on fixed hot spots [*Müller et al*., 1993; herein denoted

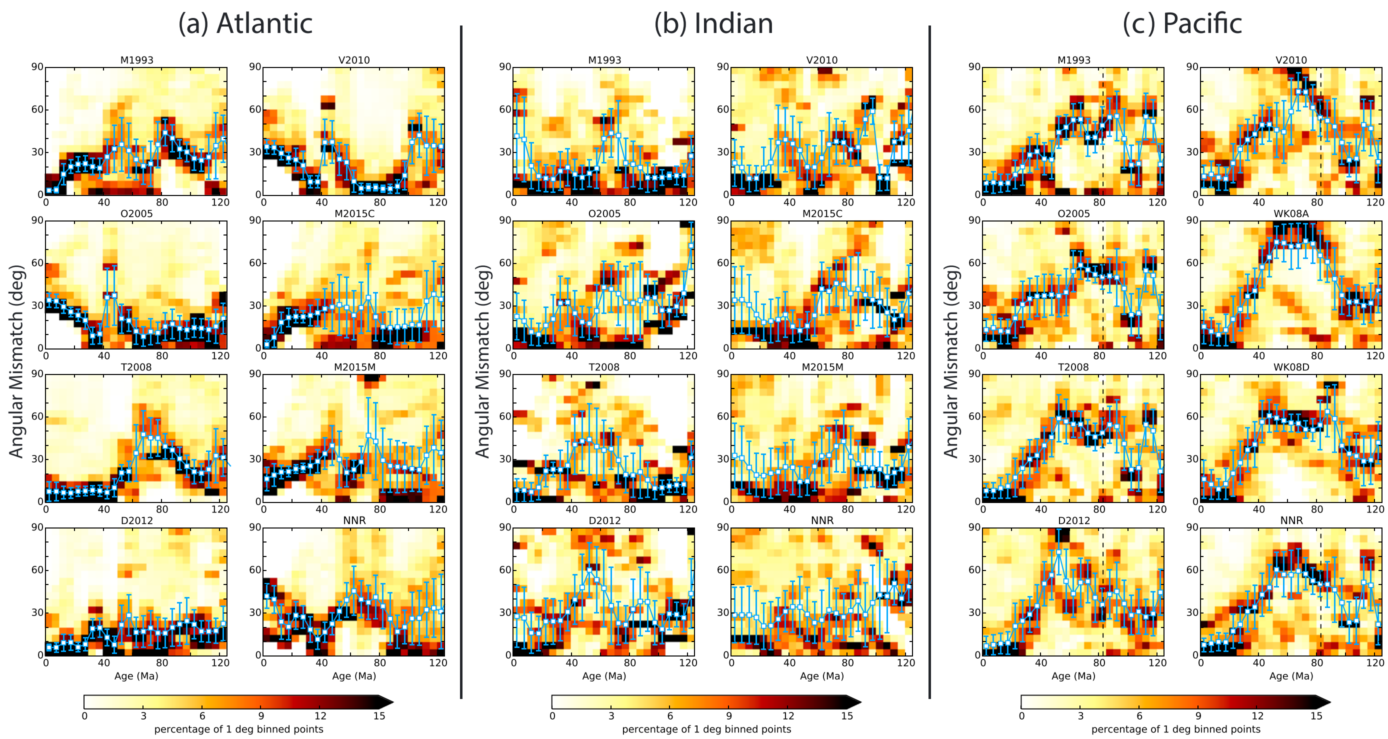

Figure 3. Histograms of the skew angle between paleospreading direction and APM at spreading ridges for the spreading preserved in the (a) Atlantic, (b) Indian, and (c) Pacific ocean basins since 130 Ma. Histograms are plotted for a range of different APM models. Values are subdivided into 5 Myr time bins, and 5° skew bins. Square symbols show median and error bars the associated median absolute deviation, for all skew values within each 5 Myr time bin. In Figure 3c, the dashed line at 83 Ma denotes the time at which Pacific APM in models defined by Africa APM switch to being constrained by WK08A stage poles. APM model abbreviations are given in the text.

M1993; *Maher et al.*, 2015] for the Indo-Atlantic realm; fixed hot spots for the Pacific plate [*Wessel and Kroenke*, 2008; *Chandler et al.*, 2012]; moving hot spots [*O'Neill et al.*, 2005; herein denoted O2005; *Torsvik et al.*, 2008; herein denoted T2008; *Doubrovine et al.*, 2012; herein denoted D2012]; slab remnant mapping from seismic tomography [*van der Meer et al.*, 2010; herein denoted V2010]; and a no net rotation (NNR) reference frame [*Williams et al.*, 2015]. The models WK08A [*Wessel and Kroenke*, 2008] and WK08D [*Chandler et al.*, 2012] are both based on fitting hot spot trails on the Pacific plate; they differ in that model WK08A attempts to fit all available data along age-progressive Pacific trails, while model WK08D does not attempt to fit the pre-Hawaii-Emperor Bend section of the trail attributed to the Hawaiian plume. Among Indo-Atlantic fixed hot spot models, we test alternative models proposed by *Maher et al.* [2015] that differ in fitting the oldest part of Reunion trail either to the Chagos-Laccadive Ridge (herein denoted M2015C) or the Mascarene Plateau (herein denoted M2015M). For model D2012 only, results were generated using the RPM model of *Doubrovine et al.* [2012] that uses an alternative plate circuit to link plate motions in the Pacific domain to the Indo-Atlantic domain from 45 to 83.5 Ma. The choice of RPM model has only a minor influence on the results.

We analyze results since 130 Ma, which marks the initiation of major, well-preserved spreading systems in the South Atlantic and Indian Oceans during the breakup of Gondwana. For each model, we represent the results for different APM models as time-dependent histograms, subdivided into the three major ocean basins (Figure 3).

Uncertainties in APM models may be associated with predictions of hot spot motion from geodynamic modeling (or alternatively, the assumption of hot spot fixity), radiometric dating of seamounts, limitations of RPM reconstructions, or the assumptions made in linking surface reconstructions to interpreted slab remnants in seismic tomography [e.g., *O'Neill et al.*, 2005; *van der Meer et al.*, 2010]. The accuracy of spreading directions within the RPM model is dependent on the availability of fracture zones, which are well imaged for all the ocean basins using gravity anomalies derived from satellite altimetry [*Sandwell et al.*, 2014].

3. Results

For all major oceans basins, we observe a general alignment of spreading and APM for young (<20 Ma) seafloor, consistent with the findings of *Becker et al*. [2015]. Median skew values (Figure 3) for the last 20 Myr are typically <20° in the Pacific for all APM models and between 10 and 40° for spreading in the Indian and Atlantic domains. Over the last 130 Myr, the time-dependent histograms illustrate a clear contrast between the results for the Indo-Atlantic domains and Pacific domain.

In the Atlantic domain, the median skew between spreading direction and APM is almost always below 45° since 130 Ma, regardless of the choice of APM model, and less than 30° for some APM models (e.g., D2012; Figure 3a). Peaks and troughs in the results vary significantly between different APM models, because for the slower APM near the Atlantic spreading ridges (illustrated by the shorter bars in Figure 2a than in Figures 2b–2c) relatively small changes in APM vectors can have a large effect on the APM direction and therefore the skew angle.

For the Indian Ocean, median skew values are dominantly <45° since 100 Ma, with a few APM models producing phases of higher median skew (Figure 3). The skew values are most coherent for fixed hot spot models, in particular, model M1993 that uses more data from Indian Ocean trails than any other considered model. Histograms for other APM models give a relatively incoherent pattern before the mid-Cenozoic. A contributing factor to the poor alignment for older times may be the decrease in preserved MOR length for Indian Ocean spreading ridges back into the Cretaceous (Figure 1c), such that the histograms for this region and time period are based on a smaller sample size and less robust.

In the Pacific domain, a strong correlation exists between APM and spreading direction at present day (5–15° skew), consistent with seismic anisotropy studies [*Becker et al*., 2014; *Beghein et al*., 2014]. However, this present-day correlation appears to be an exception rather than the rule for the last >100 Myr. The skew between the APM and spreading directions is significant for all APM models. Models that fit well the Hawaiian-Emperor bend with fixed (WK08A) or moving (D2012) hot spots predict the dominant direction of late Cretaceous-early Cenozoic Pacific spreading to be roughly orthogonal to the APM along the active MORs. The skew angle is smaller for APM models that do not predict significant changes on Pacific APM direction around 50 Ma (e.g., WK08D, M1993, and O2005), but the angle is still significant (>45°). All APM models predict that the skew angle has gradually decreased from high values in the Early Cenozoic to smaller values since ~20 Ma (Figure 3). An important aspect of the results (Table S1, Figures 3 and S1) is that Pacific APM for times older than ~83 Ma (Figure 3) is not calculated based on Africa-based APM models themselves, since the RPM model used implies that the Pacific plate is surrounded by subduction zones during this time period. Instead, the APM is based on stage poles from APM model WK08A (differences between models reflect different absolute orientation of the Pacific plate between models). Hence, the comparison for times older than 83 Ma, included here for completeness, should be treated with caution and largely reflects model WK08A.

Figure S1 shows the global skew values as a function of spreading rate and absolute plate velocity for different APM models. Skew is typically low for all but the lowest spreading rates and absolute velocities, though the trend is less clear for higher velocities where relatively few spreading segments are available (top panel of Figure S1 for each APM model). For several APM models, a bimodal distribution of skew is observed for high spreading rates, resulting from the contrast between low skew for crust formed at high spreading rates in the Indian Ocean versus higher skew for the same spreading rates in the Pacific domain. At the lowest spreading rates (<10 mm/yr) or absolute velocities (<20 mm/yr), the skew is less strongly concentrated at low angles, indicating that uncertainty in the direction of APM is amplified where plates are moving slowly.

4. Discussion

4.1. Are APMs and Spreading Directions Aligned?

A first-order observation is that the relationship between spreading direction and APM is not random, irrespective of APM model choice. The nature of the correlation varies with the APM models, the geographic region, and reconstruction time. In the Atlantic and Indian Oceans, significant correlation is observed since 130 Ma, expressed by a unimodal skew distribution with overall median values fluctuating between 15° and 31° and median absolute deviations between 10° and 22° (depending on APM model; Figure 3 and Table S1). The results suggest a very different behavior for the Pacific, with a clearer time dependence (Figure 3).

Consistent, long-term (0–130 Ma) alignment between spreading and APM is apparent in the Atlantic Ocean (Figure 3a), which has experienced a relatively simple spreading history since the Early Cretaceous. Most of the Atlantic Ocean can be characterized by a single, continuous MOR, and it is bounded by passive continental margins for much of its length, so that the contribution of ridge push forces [*Richardson*, 1992] will have remained relatively constant. A larger driving force is likely to come from slab suction [*Conrad and Lithgow-Bertelloni*, 2004] associated with long-lived subduction along the western margins of the Americas, acting to pull these continents westward in general alignment with Atlantic spreading, while spreading ridges are mostly passive features [*Becker et al*., 2015].

The Pacific domain exhibits the largest skew between APM and spreading. This is particularly true for models of Pacific motion that attempt to fit the entire Hawaii trail under a fixed hot spot assumption (WK08A), but even models that produce no significant change in Pacific absolute motion in the early Cenozoic (O2005; WK08D) show significant skewness from the end of the Cretaceous to the Eocene (~80–40 Ma). This observation raises two possibilities: either none of the APM models provide a meaningful representation of Pacific absolute motion or the strong alignment between spreading and APM in geologically recent times (Figure 3c) [*Becker et al*., 2015] is not representative of the longer-term behavior of the plate-mantle system within the Pacific domain. Modeling studies exploring the consequences of evolving plate driving forces on Pacific motion [*Lithgow-Bertelloni and Richards*, 1998; *Faccenna et al*., 2012; *Butterworth et al*., 2014] show a broad agreement between Pacific absolute motion predicted by plate boundary forces and the range of Pacific APM models shown in Figure 3c. Oceanic plate fragmentation events since 130 Ma do not suffice to explain the pattern of persistent and widespread skewness throughout the region in the Cretaceous and Early Cenozoic (Figure 2). We therefore suggest that the high Pacific skewness is due to the absolute motion of the Pacific plate relative to the deep mantle.

Because the Pacific domain is surrounded by subduction zones, the plates diverging at MORs within the Pacific domain that is surrounded by subduction zones are directly subjected to slab-pull forces that dominate their absolute motion [*Conrad and Lithgow-Bertelloni*, 2004], in contrast to the Indo-Atlantic domain. Slab-pull forces acting on these plates have varied since 130 Ma in response to evolving plate boundary configurations, including mid-Cretaceous cessation of long-lived subduction along the East Gondwana margin [*Collot et al*., 2009], subduction of the Izanagi-Pacific spreading ridge [*Whittaker et al*., 2007; *Seton et al*., 2015], and Cenozoic subduction initiation in the Western Pacific [*Gurnis et al*., 2004; *Sutherland et al*., 2010].

The Indian Ocean (Figure 3b) can be considered intermediate between the Atlantic and Pacific domains, both in terms of observed skewness and geodynamic setting. Like the Atlantic Ocean, the Indian Ocean is largely surrounded by passive margins, but it has experienced a more complex spreading history involving numerous plate boundary reorganizations [*Whittaker et al*., 2013; *Gibbons et al*., 2013] and much faster spreading rates as India was pulled northward prior to its collision with Eurasia [*van Hinsbergen et al*., 2011; *Cande and Patriat*, 2015]. The skew between spreading and APM is slightly worse for the Indian Ocean than for the Atlantic Ocean but is nonetheless clearly better than random. It also shows a strong alignment for model M1993 that places greater weight on fitting constraints from the Indian Ocean than other considered APM models. Large mid-Cretaceous skew may be ascribed to poorly constrained relative plate motions during the Cretaceous Normal Superchron, with a dramatic change in spreading direction occurring across Indian Ocean MORs around 105–100 Ma [*Matthews et al*., 2012].

4.2. Time Dependence of Skewness in the Pacific

An intriguing feature of our results is the overall trend of decreasing skew throughout the major Cenozoic plate-mantle reorganization of the Pacific domain [*Steinberger et al*., 2004; *Whittaker et al*., 2007; *Seton et al*., 2015; *O'Connor et al*., 2015]. Two end-member scenarios can be considered where a high skewness exists between paleospreading direction and APM based on deep mantle reference frames. In one scenario, upper mantle flow beneath sections of Pacific spreading ridges was much more oblique to spreading in the distant past than at present. Alternatively, upper mantle flow in these regions was orthogonal to the spreading throughout this period, in which case the direction of both plate spreading and upper mantle flow are at a high angle to the absolute motion of this entire system relative to the deep mantle. We next consider whether either of these scenarios, possibly working in combination, can be reconciled with the evolution of the Pacific plate.

Patterns of small-scale convection, proposed to exist beneath the Pacific Plate based on a range of observations [*Wessel et al*., 1994; *French et al*., 2013; *Ballmer et al*., 2013], tend to align with the shearing direction imposed by plate motion; the alignment beneath small, slow moving plates could be reduced if the underlying flow is dictated by larger surrounding plates [*Martin-Short et al*., 2015]. Modeling studies suggest that when plate motion changes, the length of time for the pattern of small-scale convection to realign to the new plate motion direction may be as little as 20 Myr, or much longer, depending on model parameters [*van Hunen and Zhong*, 2006]. Based on the trends of non–hot spot volcanic chains emplaced in Pacific crust since the Hawaii-Emperor Bend (HEB), *van Hunen and Zhong* [2006] suggested that the time scale of flow realignment is $<$40 Myr. This scenario is consistent with the general alignment of present-day Pacific APM with both upper mantle anisotropy beneath young Pacific ocean lithosphere [*Beghein et al*., 2014; *Becker et al*., 2015], and with low-velocity fingers spanning the central Pacific [*French et al*., 2013], such that any misalignment generated in the early Cenozoic or earlier is not preserved at present.

Toomey et al. [2007] explained skewness of spreading and APM at the East Pacific Rise as a change in plate motion driven by changing basal tractions imposed by mantle flow. In this scenario, changes in plate motions lag behind changes in flow direction within the upper mantle over time scales of several million years, possibly due to transpressive transform faults limiting the rate at which plate motions can adjust to plate-driving forces. It is unclear whether such a process can explain much larger spreading skewness over longer time scales, such as the gradual decline in skewness observed for the Pacific through the Cenozoic. The total transform length, and power dissipation across Pacific transforms declined in the Cenozoic [*Stoddard*, 1992], mirror the decline in skewness identified in our analysis. A major change in mantle flow (and therefore basal tractions) beneath the Pacific around HEB time could explain the peak in power dissipation across Pacific transform faults shortly after HEB, which gradually declined as transforms shortened and plate motions readjusted to the change in driving forces. Despite the sharpness of the HEB, these results suggest protracted changes in the Pacific plate-mantle system, possibly explained by a series of changes in Pacific plate motion since the HEB associated with changing circum-Pacific plate boundary forces [*Wessel and Kroenke*, 2008].

If the evolution of skewness for the Pacific domain is the consequence of a plate-mantle reorganization, then we may expect other such reorganizations to be expressed in Figure 3. Notable examples have been documented for the spreading systems around the African plate between ~50–70 Ma [*Cande and Stegman*, 2011] and a 100–105 Ma event that produced a dramatic change in direction of numerous plates involved in Gondwana breakup [*Matthews et al*., 2012]. Signatures relating to these events are difficult to discern in the results for different reference frames (Figure 3). However, APM models minimizing trench migration rates [*Williams et al*., 2015], particularly APM model T2008, reveal that for 0–70 Ma, a peak in skewness of $>$45° in the Atlantic occurs around 60 Ma, and at 50 Ma in the Indian Ocean (Figure 3). Much stronger alignment between spreading and APM both before and after these peaks is observed. For times older than 70 Ma, APM model V2010, which minimizes trench migration rates for 70–130 Ma [*Williams et al*., 2015], produces the largest changes in skewness in both the Indian and Atlantic Oceans around 100 Ma. While the large skewness values during the Cretaceous must be treated with caution due to increasing APM model uncertainties for times older than 70 Ma, our results suggest that high skewness in the Pacific may have begun to develop around ~100 Ma, perhaps due to interaction between slabs attached to the Indian and Izanagi plates, resulting in an abrupt reorganization event in the Indian basin that propagated more gradually into the Pacific realm [*Morra et al*., 2012].

4.3. Implications for Future APM Modeling

The APM models tested here define "mantle reference frames" (as opposed to paleomagnetic data without true polar wander correction, which tie plate motions to the Earth's core) linking plate motions to structures in the deep mantle. By contrast, studies of alignment between spreading directions and mantle flow typically focus on the shallow upper mantle [*Becker et al*., 2014; *Beghein et al*., 2014; *Toomey et al*., 2007]. This raises the question: should we expect the motion of plates relative to the "deep mantle," and the spreading fabric at MORs, to align with flow in the shallow upper mantle? Fixed hot spots and vertical slab sinking at a constant rate are known to be approximations, and moving hot spots are tied to specific dynamic models. Given these limitations, alternative global constraints that can be placed on APM models are attractive to complement the relatively small number of hot spot trails confined to few plates.

Our study suggests that spreading directions may help to constrain APM directions, in particular, for oceanic plates that are not directly driven by sinking slabs and in the absence of major plate-mantle reorganizations. The success in determining a reference frame from present-day plate motions and spreading directions [*Becker et al*., 2015] may reflect the lack of significant plate reorganizations in the last tens of millions of years.

None of the APM models tested here sought to optimize the alignment between paleospreading directions and APM. Thus, the degree of correlation is unbiased by prior assumptions and could be used in a new APM model seeking to optimize these alignments in a time-dependent manner, building on the approach of *Becker et al*. [2015] for contemporary plate motions.

5. Conclusions

We find evidence for alignments between seafloor spreading and APM since Pangea breakup. Alignment is observed globally for recent times (<20 Ma), extending the independent estimates for present day [*Becker et al*., 2015] back in time. Alignment since 130 Ma is strongest in the Atlantic Ocean, whereas in the Pacific Ocean, significant skew between spreading and APM is observed before 20 Ma, and an intermediate degree of alignment is observed in the Indian Ocean. We attribute these differences to the forces driving plates; skewness is largest at spreading centers where diverging plates are directly driven by slab pull. Alignment between spreading and APM may be interrupted by major plate-mantle reorganizations, as observed in all ocean basins, and most notably in the Pacific Basin during the Late Cretaceous and Early Cenozoic. Our results suggest that seafloor-spreading fabric could be used to constrain global models of absolute plate motions since the beginning of Pangea breakup, in particular, for spreading centers between large continents such as in the Atlantic.

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